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CONFLICT RESOLUTION THROUGH NEGOTIATION IN RAILWAY OPEN ACCESS MARKET: A MULTI-AGENT SYSTEM APPROACH

CHI WAI TSANG and TIN KIN HO

Department of Electrical Engineering, The Hong Kong Polytechnic University,
Hung Hom, Kowloon, Hong Kong

E-mail: tcwden.ee@polyu.edu.hk, eetkho@polyu.edu.hk
Tel: (852) 2766 6151, (852) 2766 6146
Fax: (852) 2330 1544

Abstract: Open access reforms in railways allow multiple train operators to provide rail services on a common infrastructure. As railway operations are now independently managed by different stakeholders, conflicts in operations may arise, and there have been attempts on deriving an effective access charge regime so that these conflicts may be resolved. One approach is by direct negotiation between the infrastructure manager and the train service providers. Despite the substantial literatures available on the issue, few of which have considered the benefits of employing computer simulation as an evaluation tool of railway operational activities such as access pricing. This paper proposes a Multi-agent System (MAS) framework for the railway open market and demonstrates its feasibility by modelling the negotiation between an infrastructure provider and a train service operator. Empirical results have shown that the model is capable of resolving operational conflicts according to the market demand.

Keywords: Railway open market; Track access pricing; Train scheduling; Multi-agent systems; Agent negotiation

1. INTRODUCTION

In recent years, railway regulatory reforms have been implemented in many countries where the primary objective is to introduce intra-modal competition within their railway markets. The successful reform precedents in gas, electricity and telecommunication utilities have encouraged the adoption of an open access approach. It involves distributing the management of infrastructure facilities and train operations to independent stakeholders so that multiple train-service providers can gain access to a common infrastructure by paying an access fee. A contestable railway market can therefore be achieved through the competition of track capacity and customers between the train operators.

Owing to the limited availability of track resources, the infrastructure provider has to decide which and when a service provider has the right to operate its train services. However, it is inevitable that these independently managed stakeholders will experience disputes over prices and service characteristics (e.g. train types and speeds) due to their differences in operational objectives. To resolve conflicts between the stakeholders, posted pricing, negotiation and auctioning have been proposed to associate the access charge either to the incurred usage cost or to the market expectation. Unfortunately, since most reforms are at their infancy of development, the railway industry is still striving for better means of access pricing and capacity allocation.

Most studies have aimed to analyse the existing market according to the observed outcomes from these reforms, but there has been little research devoted to evaluate the performance of the pricing mechanisms by the use of simulation and modelling. In fact, there has been even a lack of study to examine the requirements and feasibility of adopting a simulation approach.

Although this paper is not intended to compare the merits and limitations of different charging regimes, it aims to provide the necessary backgrounds to fill the gap of the need to devise a plausible evaluation tool for the railway open market. This study identifies the key modelling issues in the reformed railways and investigates the feasibility of modelling the railway open market by a multi-agent system (MAS) approach. MAS-modelling is an increasingly popular method to solve distributed problems involving entities with high degrees of autonomy, rationality and social capability. This field of study contains models for both decision-making and negotiation activities between trading parties. As a result, it provides a potentially viable approach in modelling the transaction in the open railway market.

This paper is organised as follow. Section 2 reviews the access charging and traffic management problems emerged from the railway open market. Section 3 then identifies the difficulties in modelling the competitive market and proposes a MAS framework for developing the simulation tool. Section 4 continues with modelling of a negotiation between an infrastructure provider and a train service operator. A simulation study is performed in section 5 to illustrate the capability of the model to resolve conflicts dynamically by responding to the market demand.

2. RAILWAY OPEN MARKETS

2.1. <u>Railway Competitions</u>

Railway businesses are often referred as natural monopolies and have limited competition because of the lumpiness in infrastructure provision. When a rail network is constructed or expanded, track capacity is often created in large incremental step (lump) relatively to the unit consumption by the train services. In other words, the newly built infrastructure can support a large increase in traffic volume. Since the fixed investment cost is recovered from the actual rise in demand, the average cost of transportation declines when traffic volume increases over the range of additional capacity. Consequently, it is usually cheaper to provide train services when the entire demand is captured by a single operator (Fig. 1).

In the recent decades, there has been a change in perspective that competition is possible for train operations (above-rail activities) even though infrastructure provisions (below-rail activities) may elude. The barrier to competition may therefore be lowered by allowing multiple train service operators to gain access to the infrastructure from a common provider. Countries such as Argentina and Japan have adopted a third-party access approach in which external train operators have mandated right of entry to a vertically-integrated railway [1, 2]. In other words, apart from the trains operated by the infrastructure owner, other parties may also run trains on the same track. Alternatively, other places like Sweden and UK have sought for open access reform, where train operations are completely separated from infrastructure provision [1, 2]. These new market structures allow competition between train operators, and some of which have also introduced additional competition in ancillary services such as rolling-stock leasing and maintenance service provision.

Introducing above-rail competition is considered to be an effective means to reduce expenditure and increase revenue [3]. A competitive market can provide more choices to the consumers which creates pressure for the stakeholders in their spending. The stakeholders are also pressed for developing innovative plans and services so as to exploit new markets and maintain profits. Despite these ideal benefits of competition, the access reform in railways has generated new challenges in deriving the access charge and resolving conflicts in traffic management.

Insert Figure 1 about here.

2.2. Access Pricing Policies

Posted pricing, direct negotiation and auctioning are the three proposed mechanisms to access charge setting. In posted pricing, charge rates are established in advance and published to the access seekers. The tariff is often composed of a basic charge in terms of the vehicle-kilometre or gross tonne-kilometre transported, and an uplift cost that is levied according to the operating characteristics (e.g. freight/passenger services and type of rolling-stocks). In direct negotiation, the infrastructure provider and the train operator take turns to make concessions on issues including access charge, train schedule and operating characteristics until both stakeholders agree on the terms of usage. For auctioning, capacity is pre-packaged into various sets of non-conflicting train paths to allow interested seekers to bid at their most preferred prices. The operator with the highest bid will obtain the train paths under a set of restrictions.

Apparently, posted pricing provides train operators with more certainty in managing their businesses, but the infrastructure provider may fail to discriminate train operators with different operating requirements effectively. For example, trains travelling at different speeds may be charged identically even though they have different traction energy and peak demand requirements. Conversely, services with identical speed specifications but scheduled on different traffic environments might also be charged at the same price despite having different capacity consumption (see below). On the other hand, direct negotiation and auctioning have better capability to distinguish operators with respect to their willingness-to-pay for the right-of-ways. Nevertheless, experiences have suggested that negotiated pricing can sometime required timely and costly transactions, while auctioning has never been employed in practice because of the difficulty in devising train paths that simultaneously suite the requirements of several train operators [2]. These existing regimes have their merits and limitations, and the railway regulators and stakeholders are still striving for better alternatives whenever possible.

2.3. Conflict Resolution in Resource Allocation

Along with determining a suitable pricing regime, the infrastructure provider also needs to formulate a conflict-free and preferably efficient resource allocation plan for the access seekers. Since the train operators are independently managed, they will occasionally request overlapping train paths. The infrastructure provider then has the responsibility to resolve their disputes in right-of-way.

Efficient allocation is complicated by heterogeneous traffic condition (i.e. when trains are operating with a wide range of speeds). Fig. 2 illustrates the effect on capacity utilisation when the traffic demand is homogeneous or otherwise. Capacity utilisation is defined as the ratio of the time taken in operating a set of trains with their minimum headways (i.e. A and B) to the time taken in travelling at their actual timetables (i.e. W) [4]. Clearly, when trains running at different speeds are scheduled together, more capacity is needed to generate the same number of services ($B/W > A/W$).

In principle, the cost of additional capacity consumption may be recovered from the access charge. However, the predefined tariffs in posted pricing are unlikely to respond to the ongoing changes in relative train speeds in the competitive market. On the contrary, direct negotiation is able to provide a means to dynamically compute the associated costs of capacity utilisation and traction power supply. Therefore, the access charge can be more appropriately recovered by negotiation if a high transaction speed is available. In addition, negotiation allows the operational train speeds to be determined by the requirements of the access seekers. If the service providers are willing to afford a higher tariff, heterogeneous traffic may be allowed, otherwise the infrastructure provider may offer a cheaper access charge for capacity saving.

Maintenance costs of track and rolling-stock is another potential conflict to be resolved. There is an indivisible relationship between rails and wheels. Poor rail quality will induce an increased rolling-stock maintenance cost and vice versa. In a 'closed' railway market, the maintenance cost on rails can be balanced with the investments on rolling-stock's quality. However, with the separation of responsibilities, service providers may tend to keep maintenance on vehicles minimum so as to reduce their operating costs. In order to recover the imposed maintenance fee, the infrastructure provider has to decide whether to raise the access price to reflect the actual damages on track or to restrict the use of track to better maintained rolling-stocks.

Insert Figure 2 about here.

3. METHODOLOGY

3.1. Modelling and Computer Simulation

There is a need to derive effective access pricing regimes to resolve disputes between railway stakeholders. Various post-evaluations have been conducted with respect to regulatory efficiency [1], train planning process [5] and accounting performances of stakeholders [6]. Findings derived from these studies can be applied in future improvements in the system, which is followed by a new cycle of post-evaluations. Unfortunately, the timely and costly execution often hinders the actual implementation of these new findings.

With the advance of fast computing technologies, computer simulation is a cost-effective means to evaluate a hypothetical change in a system. For example, simulation suites have been developed to study a variety of traffic control strategies according to sophisticated models of train dynamics, traction systems and power systems [7]. Simulation therefore allows pre-evaluation studies and avoids irreversible changes to the physical system. Consequently, it is beneficial if the open market can be modelled in a similar manner to assist future improvements in railway operation.

A simulation model is a representation of the behaviour of a system that can be executed in a computer. Most simulation models are devised and implemented as a single (or central) computation unit which derives the expected system outputs by processing the user-specified inputs with an algorithm. However, the idea of central evaluation is inappropriate for the railway open market due to the following characteristics.

3.1.1. Distributed self-interested entities

As a result of railway reforms, resource planning is now a distributed rather than a centralised problem and different stakeholders will inevitably attempt to optimise their internal benefits. In fact, each of these optimisations are likely to involve multiple attributes such as cost and travelling times, and are subject to constraints derived from business (e.g. availability of rolling-stock supply), engineering (e.g. maximum line speeds) and regulations (e.g. regulated ceiling and floor prices). Some of these constraints and their business objectives are not revealed to other stakeholders to avoid possible loss of advantage during the business transactions.

A suitable modelling framework should therefore enable the representation of the stakeholders as separated entities with individual control over their information, decisions and actions. The framework should also allow separate local simulation models for solving the distributed multi-dimensional constrained optimisation problems.

3.1.2. Co-ordination via bargaining

Despite the isolated control over their activities, the stakeholders are still inter-dependent during the formulation of train timetables. In the case of negotiation, the stakeholders will attempt to persuade their negotiating partner to align with their operational objectives through bargaining. To resemble the natural process of resolving conflicts, the modelling of the co-ordination activities is of utmost importance. As a result, apart from the distributed framework, there are additional requirements on modelling the interactions between the local entities, but classical simulation models are generally not designed to capture these behaviours.

3.1.3. Rationality of local entities

In principle, solving the local optimisation problem may take advantage of the classical simulation models. The rational decisions may be the outputs of the local model while the operational objectives of the stakeholder can be considered as the user-specified inputs. However, the choice of algorithm is complicated by the additional inputs from the responses of its interacting entities which can only be determined during runtime. These algorithms therefore require a certain degree of flexibility so that the distributed entities may decide the best actions dynamically without human interferences.

Apart from being responsive to the changing environment, another dimension of rationality is proactiveness. The local entities should be able to inspect their internal status and initiate activities (e.g. promotion of idle resources) which are consistent with their business goals in order to enhance the competitiveness of the stakeholders.

3.2. Multi-Agent System

Multi-agent system (MAS) modelling is a sub-field of Distributed Artificial Intelligence (DAI). While classical AI focuses on mimicking the problem solving ability of individual organism in machines, DAI concentrates on more complex problems which are inherently distributed, where knowledge and activities are separated naturally in space [8]. Each entity in the group has problem-solving capabilities but the entire problem cannot be solved by a single entity. By coordinated interaction, the entities resolve the complex problem in a timely and efficient manner [9]. In particular, MAS allows both co-operating and competing interactions. Co-operative entities work towards a common goal while competing entities possess individual ones.

The entities in MAS are called agents. By definition, an agent is an encapsulated computer system, situates in some environment, and can act flexibly and autonomously in that environment to meet its design objectives [10]. Thus, an agent is a piece of software-driven hardware that can only work in some predetermined application domains (i.e. they are not 'super-agents'), but provided that it is operating in these domains, it can handle its designated tasks rationally, and adapt to changes in a flexible manner without human interventions.

There are increasing applications of MAS in engineering systems such as e-commerce [11, 12], data-mining [13, 14], and supply-chain management [15, 16]. In addition, there is a growing interest in applying MAS in transportation systems [17]. In these applications, it is difficult to study and explain the complex system without modelling the intentions and activities of the local individuals (e.g. people, vehicles and companies) because the ultimate system behaviour emerges from the interactions among these entities. The notion of a system composing of autonomous agents allows these complex systems to be studied from a 'bottom-up' approach.

With the emergence of sophisticated agent development software such as JADE [18] and FIPA-OS [19], the development time of software agents can be considerably reduced. These software toolkits mainly provide generic agent services regarding to communication, resource control, data access and encodings. Nevertheless, developers are still required to devise the local agent structure and their communication scheme. These may be adopted from the agent modelling techniques (e.g. BDI model [20]), but it is also possible to apply analytical or AI models for agent reasoning.

Another important concern when designing a MAS is the size of the agent community. For example, a system could have only one layer of agents to represent the companies along a supply-chain, but it is equally feasible to expand two more layers for the departments within the companies and the staff working in the departments. The three-layered approach clearly requires a higher demand in modelling the autonomy and interactions of the agents, but more detailed studies can be performed at the department level and the personnel level. Thus, the granularity of the agent society depends on the depth of study required.

3.3. Modelling Railway Open Market with MAS

Given its characteristics matches with the requirements in distributed self-interested entities, co-ordinated behaviours and local intelligence, MAS provides a suitable conceptual framework for the railway open market. A realisation of MAS for railway resource management is illustrated in Fig. 3.

This model contains one level of agents to represent the stakeholders in the railway market. In addition to the infrastructure provider (IP) and train service providers (TSP), the model may also include ancillary companies, like rolling-stock providers (RSP) and maintenance service providers (MSP). These stakeholders assign their confidential information such as cost curves and operational tactics to their corresponding software agents before they are connected to a common communication platform. When an agent joins the platform, it is registered to the Directory Facilitator (DF) agent whose function is to maintain an updated record of the agent addresses and the services they provide. A stakeholder agent may therefore recognise the existence of other agents by performing a query to the DF.

An agent on the platform will either be perceived as a resource provider or a purchaser without deliberating its internal status to the other agents. The agents on the platform are not expected to share a common goal, but they may form temporal association to examine whether a sale of resource is feasible and beneficial according to the pre-assigned criteria of the stakeholders.

The framework may be used to conduct useful simulation studies in several levels. Firstly, the agent community can allow the study of the effects from different degrees of competition by altering the number of resource providers and/or purchasers. This may aid the railway regulator to determine the correct degree of competition in railways. Secondly, different transaction policies (e.g. posted pricing, negotiation and auctioning) can be formulated and tested to improve the charging regime. Further studies may also be performed to evaluate the impacts from any proposed changes in regulations, business objectives and engineering operations by modifying the rational behaviour of the agents. For instance, constraints as a result of regulatory changes can be added locally to the relevant agents, and modification on business objectives and scheduling mechanism may be achieved by adjusting the internal cost functions and implementing a proper mathematical model respectively. Results from these simulations may be used to improve capacity utilisation and competitiveness of the stakeholders.

It is also valuable to note that agent modelling can also be applied in third-party access market. In this case, one of the TSP agents will be possessed by the same stakeholder of the IP agent. However, as most regulations will prevent unfair gain of track access by the incumbent owner of the infrastructure, the above and below railway activities will still be separately managed by different departments within the company. As a result, the two departments can still be modelled as separate agents.

Insert Figure 3 about here.

4. DEVELOPMENT OF MAS

Conducting the entire study above requires extensive and detailed modelling of the individual agents and their interaction. While it is beyond the scope of this paper to construct and analyse the MAS depicted in Fig. 3, a brief model for the direct negotiation between IP and TSP is given in this section to demonstrate the development of railway agents in the framework described.

4.1. Communication Model

The negotiation scheme between a TSP agent and an IP agent is adopted from a fuzzy constraint based model [21]. The possible agent actions and their relationship are illustrated in Fig. 4. In this model, the bargaining process for a product is resolved as a prioritised fuzzy constraint satisfaction (PFCS) problem between a buyer and a seller. The buyer agent needs to obtain a product possessing several attributes (e.g. price, dimensions and colour), but their exact values will depend on the availability of the supply. The agent therefore reserves a set of criteria on the attributes, which is modelled by a set of prioritised fuzzy constraints. During the negotiation, the buyer agent has to specify its requirements on these attributes by submitting a selected set of crisp constraints (inequalities) to the seller agent via a FIND message. The role of the seller agent is to generate a feasible offer according to the set of constraints and its own benefits. When an offer is found, a CHECK reply is issued. Otherwise, a RELAX message is sent and the buyer is prompted to modify one of the submitted constraints, which corresponds to making a concession. However, even when an offer is generated, the buyer agent has the right to reject the product if the offer does not satisfy its requirements or if it cannot comply with the restrictions attached with the product. In the former case, a FIND message enveloping a constraint on a new attribute will be forwarded to the seller agent, while in the latter case, a REFIND message will be issued and the seller will be asked to generate a new offer. The negotiation is terminated by either an acceptance of a product (DEAL) or a failure in generating a feasible offer over the entire negotiation space (FAIL).

This model is suitable for the IP-TSP transaction because it provides the TSP (buyer) with a means to deal with uncertainties due to the IP (seller). For example, track access charge is often related to the market supply. If track capacity is limited, the TSP may either raise the payment or select another schedule where capacity is available. However, this information is unavailable until the negotiation has proceeded. By allowing a range of preference on the attributes, it creates the possibility of trade-off between certain attributes, which increases the chance of striking an agreement.

Insert Figure 4 about here.

4.2. Definition of Product (Track Access Right)

A track access right consists of a feasible train schedule, an operable rolling-stock and a flex level used in timetable reallocation (a parameter denoting the flexibility that the IP can revise the TSP's schedule when track capacity approaches to limitation). In order to obtain the right of access, a TSP needs to pay a track access charge (TAC) to the IP. The product P under negotiation can therefore be defined by Eq. (1):

$$P = \langle c, \Psi, \omega, \phi \rangle \tag{1}$$

where c is the access charge [$]; $\Psi = \langle S, \zeta, T_D, T_R \rangle$ is the train schedule consisting of the set of visiting stations $S = \{s_i \mid i = 1, ..., n_s\}$, the arrival time at the first station ζ [hh:mm], the set of dwell times [min] $T_D = \{t_{Di} \mid i = 1, ..., n_s\}$ and a set of inter-station runtimes [min] $T_R = \{t_{Ri} \mid i = 1, ..., n_s - 1\}$; $\omega \in \Omega = \{\omega_i \mid i = 1, ..., n_r\}$ is the selected rolling-stock and $\phi \in \Phi = \{\phi_i \mid i = 1, ..., n_f\}$ is the selected flex.

4.3. TSP Model

The prioritised fuzzy constraint model [21] for the buyer agent is extended in a previous study [22] in order to model the specific objective for a railway TSP. In that study, the satisfaction on the track access charge c and train schedule Ψ are represented by a set of fuzzy membership functions $\mu_i(X),\ i = 1, ..., m$ and $X \in \{c, \Psi\}$, from which the crisp constraints are derived. A crisp constraint $x^a \leq x \leq x^b$ on an attribute x is denoted by the bounds $[x^a \mid x^b]$. At the beginning of the negotiation, these constraints are set at the most preferred values $\{\hat{c}, \hat{\Psi}\}$. A TSP agent's decision to make a concession corresponds to reducing the lower limit x^a or increasing the upper limit x^b of a particular attribute. Also, since the TSP may perceive some attributes to be more important over others, a priority value $\rho_i \in [0, 1], i = 1, ..., m$ is associated with each attribute.

Given an offer $P' = \langle c', \Psi', \omega', \phi' \rangle$ received from the IP agent, the acceptability of the product is modelled by Eq. (2):

$$\alpha(X') = \min_{1 \leq i \leq m} \left\{ 1 + \frac{\rho_i}{\max\limits_{1 \leq j \leq m} (\rho_j)} [\mu_i(X') - 1] \right\}, \quad X' \in \{c', \Psi'\} \tag{2}$$

However, even if the access charge and schedule times are acceptable, the TSP may not satisfy with the restrictions in rolling-stock type and flex attached with the offer. Consequently, the TSP agent also maintains two set of fuzzy values $F_\omega = \{f_{\omega_i} \mid i = 1, ..., n_r\},\ f_{\omega_i} \in [0, 1]$ and $F_\phi = \{f_{\phi_i} \mid i = 1, ..., n_f\},\ f_{\phi_i} \in [0, 1]$ to indicate its degree of obedience to the rolling-stock and flex proposed. The overall obedience level with respect to $P' = \langle c', \Psi', \omega', \phi' \rangle$ is defined by Eq. (3):

$$\beta(\omega', \phi') = \min\{f_{\omega'}, f_{\phi'}\} \tag{3}$$

An offer is acceptable if it satisfies Eq. (4), where $\tau \in [0, 1]$ is the accepting threshold specified by the user. When $\tau = 0$, there is a better opportunity for a successful negotiation because the TSP agent may concede over the entire range specified by the fuzzy membership functions. On the other hand, when $\tau = 1$, the TSP agent will only accept the most preferred schedule defined by the user.

$$\min\{\alpha(X'), \beta(\omega', \phi')\} \geq \tau \tag{4}$$

4.4. IP Model

The task performed by the IP agent is modelled as a combinatorial optimisation problem [23]. Given the discrete nature of the attributes in the definition of track access right and the objective of maximising the benefit of the infrastructure provider, a combinatorial optimisation problem is set up. The objective function is to maximise the TAC received from the TSP and reduce the demand in capacity utilisation $\Delta\eta$ as shown in Eq. (5):

$$\max \ U = c - w_{\eta}\Delta\eta \tag{5}$$

where w_{η} is the unit valuation of capacity consumption [$].

The access charge is derived internally by the IP agent and is a composite charge consisting of track usage charge (TUC), traction energy charge (TEC), peak demand charge (PDC) and congestion charge (CGC) as defined by Eq. (6), (7), (8) and (9) respectively.

$$TUC = c_1^{\omega} n_v^{\omega} \sum_{i=1}^{n_s - 1} L_i \tag{6}$$

where c_1^{ω} is the charge rate [$/veh-km] for rolling-stock ω; n_v^{ω} is the number of vehicles of the rolling-stock; L_i is the length of track [km] in inter-station run i.

$$TEC = c_2 E(\omega, \Psi) \tag{7}$$

where c_2 is the charge rate [$/kWh] for electricity consumed; $E(\omega, \Psi)$ is the unit of energy consumed [kWh] when rolling-stock ω is running at schedule Ψ;

$$PDC = c_3 \Delta P(\omega, \Psi) \tag{8}$$

where c_3 is the charge rate [$/MW] for the increase in peak demand, $\Delta P(\omega, \Psi)$ is the increase in peak demand [MW] when rolling-stock ω is running at schedule Ψ;

$$CGC = c_4 d_{\phi} \sum_{i=1}^{n_s - 1} A_i \exp(\eta_i) \tag{9}$$

where c_4 is the charge rate [$/min] for the expected delay caused in the network, d_{ϕ} is the discount factor associated with flex ϕ; A_i is a track specific constant.

The optimisation problem defined in Eq. (5) is subject to the availability of capacity. If the requested train schedule is occupied by other train services, the schedule is considered as infeasible. Since the aim of the study is to demonstrate the capability of the modelling framework rather than to devise an efficiency search algorithm, exhaustive search has been used to determine the optimal solution.

5. SIMULATION SETUP AND RESULTS

The railway agents in this simulation are implemented in JADE [18] version 3.2. Three IP agents are constructed according to Table I. It contains the settings on the capacity valuation weighting and the relevant charge rates. Three types of rolling-stocks and flex levels are available for all negotiations, and the respective train lengths and discount factors are also included in the table. The agents are assumed to have committed 3 train schedules (Fig. 5) prior to the negotiations.

Table II further defines 7 TSP models, which display the most preferred train schedules and access charges, together with a set of assigned priorities over the attributes. The fuzzy values on the 3 available types of rolling-stock and flex are set to indicate the agents' obedience level to the respective restrictions. In addition, all agents have identical acceptability threshold of 0.1 to avoid the possible failure in obtaining a track access right.

These agents are then paired up according to Table III to simulate 8 bilateral IP-TSP transactions. The train path of interest consists of 3 inter-station runs serving a set of 4 stations named A to D (Table IV). The distance between the stations B and C is relatively long to simulate the railway transportation between 2 distanced cities.

Insert Table I about here.

Insert Figure 5 about here.

Insert Tables II, III and IV about here.

5.1. **Study 1: Conflicts in Right-of-way**

In this study, the 2 TSP agents require the same set of preferred schedule times and access charge. TSP-1 denotes a service provider with passenger-centric operational objective having high commitment to punctual station dwell times and inter-station runtimes, whereas TSP-2 aims at cost-reducing with high priority on the access charge and service start time (to reduce idle time cost of rolling-stock). Both agents negotiate with the same infrastructure provider agent IP-1, but their preferred schedules are in conflict with the second train service shown in Fig. 5a. The study therefore tests the ability for the agents to resolve conflicts in right-of-way.

The results of the negotiation are depicted in Table V, and the resultant train schedules are illustrated in Fig. 6. TSP-2 is able to acquire a schedule with no idle time (in operation at 07:50) and at a lower tariff, fulfilling its objective in cost reduction. On the other hand, given the unavailability of track capacity, TSP-1 is unable to obtain the preferred dwell times and runtimes, even though it is willing to pay a higher fee. Nevertheless, the train service of TSP-1 has avoided causing passenger dissatisfaction on short alighting times at the first 2 stations by extending the station dwell times. The increased in journey time is neutralised by the delay in service start time (at 07:52). These differences in commencing time and dwell times have caused the overtaking of the conflicting train occurred at stations B and C for TSP-2 and TSP-1 respectively.

The variations of the resulting schedules are related to the priority assignment. TSP-1, the passenger-centric agent, relaxes its constraints in the order of cost, start time, runtimes, and dwell times as specified by the assigned priorities. On the other hand, TSP-2 relaxes its constraints in the reverse order. When the TSP agents encounter a RELAX message, TSP-2 will first broaden the feasible range on dwell times, but TSP-1 will maintain the preferred times and compromise with a higher access charge. Eventually, the differences in relaxation have led to broader acceptable ranges in dwell time at stations A and B for TSP-2 (4-7 minutes) and stricter for TSP-1 (5-6 minutes). By employing the shorter dwell times of 4 minutes, the train service of TSP-2 is able to overtake the conflicting service at station B.

The schedule secured by TSP-2 also reduces the TAC mainly through the avoidance of the train operation close to 08:30 when the peak demand is highest. This is reflected by the lower PDC of TSP-2 shown in Table V. In addition, although the train service of TSP-2 consumes more capacity, the congestion charge (CGC) is cheaper when a higher flex level is accepted.

The agents are therefore able to resolve conflicts according to their operating objectives. It is also important to point out that during the negotiation, the TSP agents are aware of neither the right-of-way conflicts, nor the existence of the peak demand. Also, the TSP agents have no cooperative intention to compromise with the IP on such issues. However, by offering different schedules at different prices, the TSP agents indirectly respond to the availability of the market supply. The IP agent also derives suitable schedules according to the willingness-to-pay of the TSP agents.

Insert Table V about here.

Insert Figure 6 about here.

5.2. <u>Study 2: Conflicts in Capacity Incentives</u>

This study attempts to demonstrate the ability of the IP agent to respond to demands with different capacity incentives. Three TSP agents are set up to negotiate with IP-2, but unlike the previous study, the required train times are not in conflicts with the scheduled services. While the requested schedule of TSP-2 is set to be homogeneous to the existing traffic, TSP-3 and TSP-4 prefer shorter inter-station runtimes (i.e. heterogeneous demand). In other words, there is a conflict in capacity incentives between the IP agent and the 2 TSP agents. Moreover, priorities of TSP-3 and TSP-4 are cost-reducing and passenger-centric respectively so that they differ in their operational objectives. The capacity weighting of the IP agent is increased from 8000 to 10,000 units to enhance the effect due to capacity consumption.

Table VI shows the results of the 3 negotiations. All 3 schedules are different with respect to the travelling times, but they share common restrictions on rolling-stock and flex. The inter-station runtimes for TSP-2, TSP-3 and TSP-4 are {8, 70, 7}, {6, 68, 6} and {6, 67, 6} respectively. When compared to their most preferred runtimes of {8, 70, 7}, {6, 65, 5} and {6, 65, 5}, only TSP-2 is able to obtained all of its most preferred values. TSP-4 needs to extend its service runtimes slightly, but TSP-3 requires considerable increase in journey time. In spite of the preferred shorter inter-station runtimes for TSP-3 and TSP-4, capacity utilisation in the 2 cases is slightly higher than that of TSP-2.

Clearly, the minimum capacity consumption by TSP-2 is resulted from its inter-station runtimes being compatible with those of the existing services. As mentioned, these trains may be scheduled to operate at the minimum headway so that more services may be scheduled on the track (Fig. 2a). TSP-3 and TSP-4 do not lead to optimal allocation in term of capacity since their service runtimes deviate from the existing traffic. This is consistent with the principles in scheduling heterogeneous traffic.

Between the two agents requesting for heterogeneous train services, IP-2 also has the ability to propose different train schedules according to their willingness-to-pay. At the end of the two negotiations, the upper access price limit of TSP-4 is higher than that of TSP-3 by $50. Being able to collect a higher TAC, TSP-4 is granted with a schedule that consumes more capacity and leads to more favourable train operating times from the TSP agent perspective.

In other words, the IP agent can decide to allocate capacity 'on-the-fly'. As long as the TSP is willing to pay for its consumption on capacity usage, the request will be granted. Otherwise, the TSP will be required to compromise with more homogenous traffic condition. Rationality in capacity utilisation is therefore captured by the IP agent.

Insert Table VI about here.

5.3. <u>Study 3: Conflicts in Maintenance Incentives</u>

Similar to study 2, this study involves 3 IP-TSP transactions. However, instead of having different preferred schedule times and operation objectives, the TSP agents have different choices on rolling-stocks. TSP-5 is willing to accept any of the 3 available rolling-stocks, whereas TSP-6 accepts either ω_2 or ω_3, and TSP-7 is the most restrictive as it accepts ω_3 only. These rolling-stocks have increasing track usage charge rates of $0.04/veh-km, $0.08/veh-km and $0.12/veh-km.

The track access charges of the 3 schedules obtained are negotiated as $1657, $1748 and $1845 respectively. Inspecting Table VII reveals that the cause of the difference is contributed by the TUC. Having the lowest TUC of $94, TSP-5 is able to obtain its target schedule at the lowest charge. On the other hand, the TUCs for TSP-6 and TSP-7 are two and three times higher than that of TSP-5. Such increases in the TUCs are apparently resulted from the different charge rates. The IP agent is therefore able to associate the rolling-stocks' condition with the track usage rates. The better conditions of ω_1 reduce the rail maintenance cost of the IP. As a result, the IP is willing to offer TSP-5 the schedule at a lower tariff. As TSP-6 and TSP-7 become more restrictive on their choices of rolling-stock, they are required to pay a higher charge accordingly.

This study demonstrated the tug-of-war between a TSP and an IP on maintenance cost. When a TSP agent is determined to use a rolling-stock of poorer quality, the IP agent avoids cross-subsidising the track maintenance cost by raising the TAC. The higher track usage rate may therefore use to control the track maintenance required from the IP.

Insert Table VII about here.

6. CONCLUSIONS

We have presented a MAS framework to model an open railway market. Based on this framework, an agent negotiation between an IP and TSP has been modelled. The simulation results have shown that these agents are able to settle the track access charge, schedule times and restrictions autonomously according to their assigned operational objectives. By responding dynamically to the willingness-to-pay of the TSP agents, the IP agent is also capable of resolving conflicts in right-of-way and deriving solutions for differing incentives in capacity utilisation and maintenance cost.

Agent modelling can therefore be a plausible means to capture the functional and behavioural requirements of the stakeholders. However, it is not the intention of this work to suggest replacing the stakeholders with software agents in real-life transactions because the actual interactions between humans are certainly more complicated than the model given in this study. Nevertheless, the continuation of development of the proposed framework is expected to provide a sensible tool to conduct critical analysis prior to the physical implementation of a regulatory or operational change.

The presented work is a catalyst for further research works on enhancing the capabilities of the agents. Agents modelled in this study are not incorporated with learning capabilities to adjust the satisfaction values and charge rates during the negotiation. For example, the TSPs may not intend to adopt a fixed operational strategy (e.g. passenger-centric/cost-reducing) in their agents, but allows them to determine their behaviour according to the availability of track capacity supply. By analysing the replies from the IP agent, the TSP agents may attempt to deduce whether the required track capacity has been occupied. In this case, a passenger-centric TSP agent will have no reason to insist on its requirements and may opt for reducing the cost of expenditure. On the other hand, the IP agent can learn from the TSP agent's response and promote the idle resources proactively by lowering the relevant charge rates.

In addition, there is a substantial need for devising a faster algorithm in generating a train schedule by the IP agent. The time needed for simulations by the exhaustive search algorithm becomes impractical when the solution space is expanded by more stations, rolling-stock types and flex-levels. This is especially important because negotiation is an iteratively process in which the algorithm will be frequently used. Since the optimisation problem is combinatorial, branch-and-bound algorithm and dynamic programming are the potentially deterministic methods for further evaluations.

More complicated negotiations can also be modelled and studied. For instance, track capacity may be better utilised if the IP agent can interleave between negotiations with different TSP agents. With more information over the spectrum of demand, the IP agent can determine a better sequence to conduct the negotiations. It is valuable to compare the performance in complexity and efficiency of this mechanism against auctioning of train paths where the IP agent is also handling multiple-transactions with different TSP agents simultaneously. In addition, the MAS framework can also include RSP and MSP agents to enrich the simulations of the entire supply chain and study the effect of different level of competition in the market.

Acknowledgements

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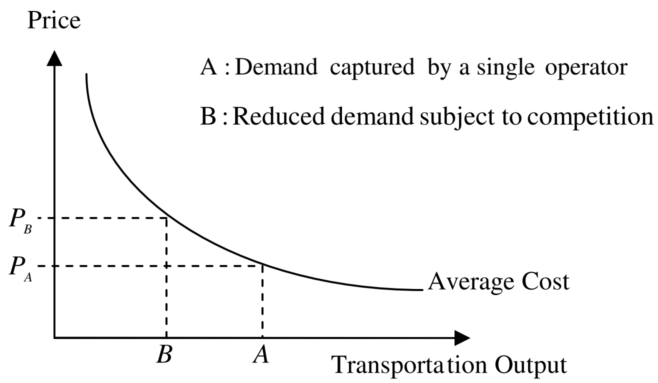


FIGURE 1 Average cost curve

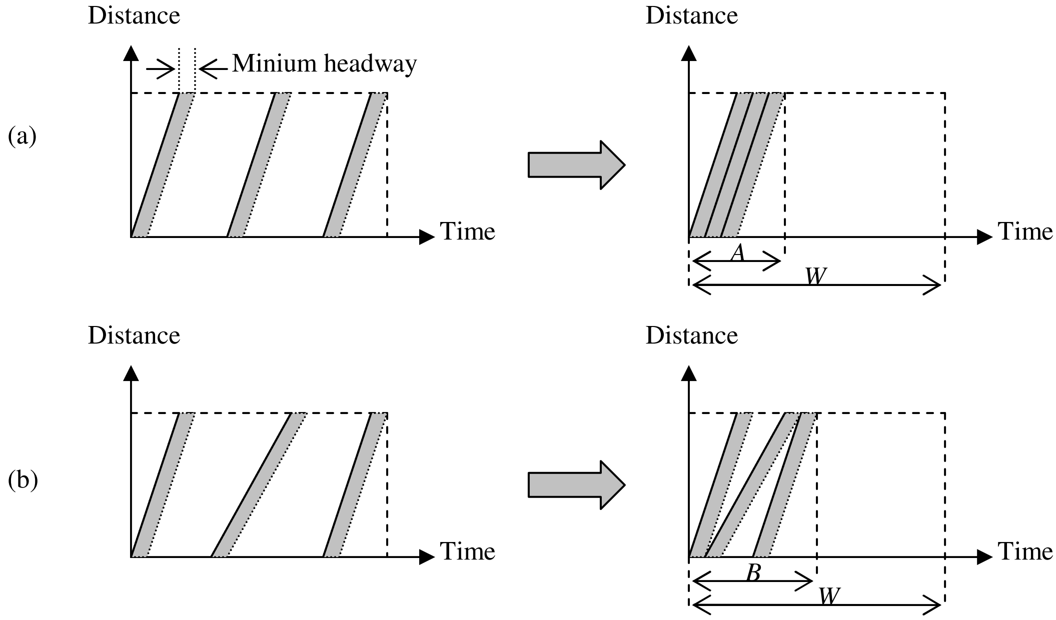


FIGURE 2   Capacity utilisation of (a) homogeneous traffic (b) heterogeneous traffic

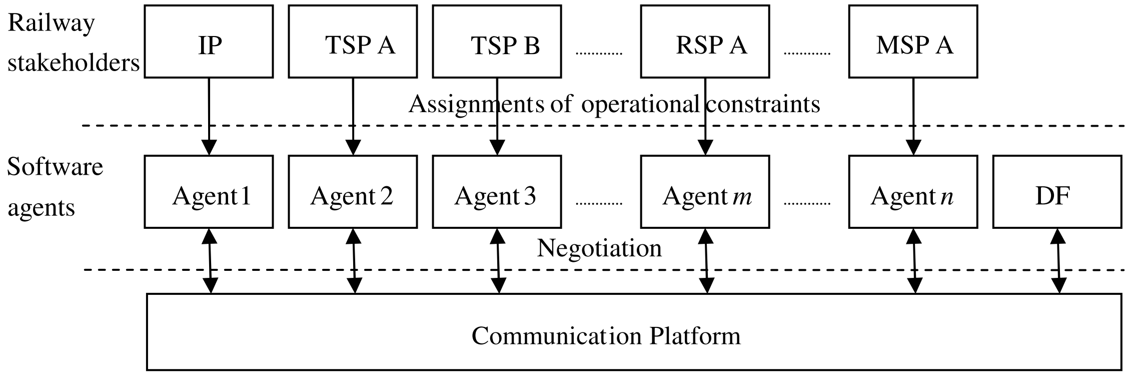


FIGURE 3 Multi-agent system framework for railway open market

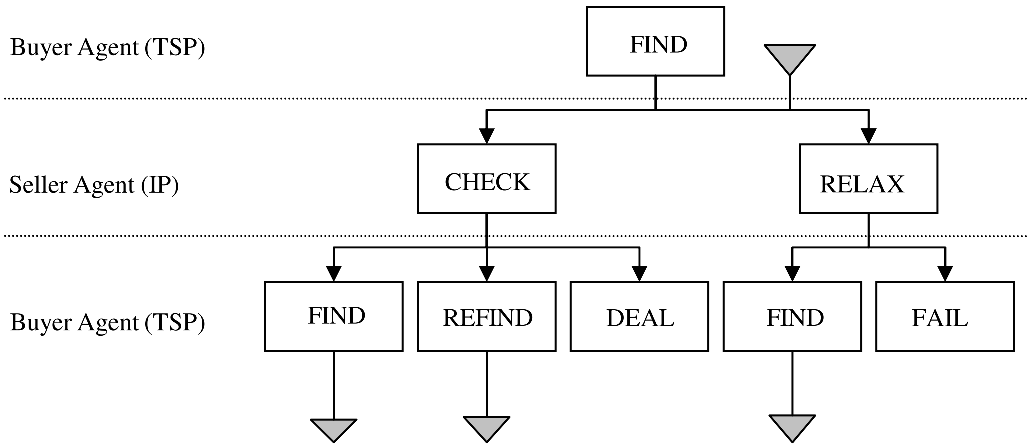
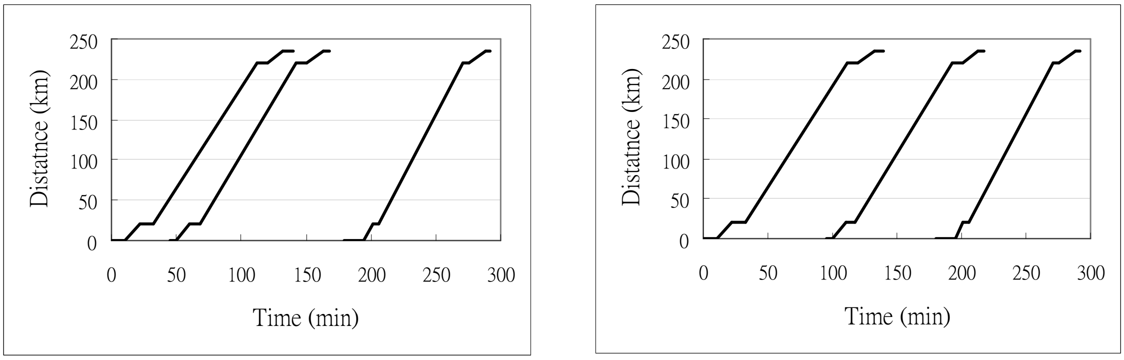
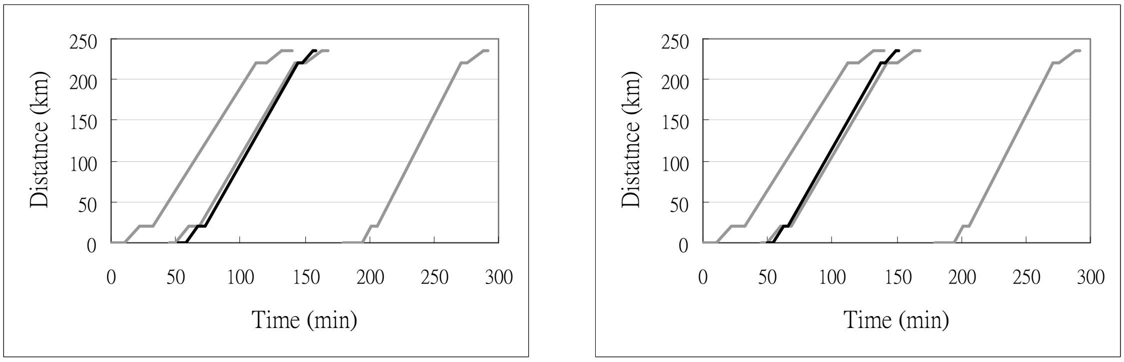


FIGURE 4   Negotiation flow with PFCS



(a) TFF - 1 (b) TFF - 2

FIGURE 5 Committed train schedule prior to negotiation



(a) Case1 (b) Case 2

FIGURE 6 Committed train schedule after negotiation

TABLE I IP models

Attribute	**IP-1**	**IP-2**	**IP-3**
w_η [$]	8000	10,000	10,000
$c_1^{\omega_1}$ [$/veh-km]	0.04	0.04	0.04
$c_1^{\omega_2}$ [$/veh-km]	0.06	0.06	0.08
$c_1^{\omega_3}$ [$/veh-km]	0.16	0.16	0.12
c_2 [$/kWh]	0.05	0.05	0.05
c_3 [$/MW]	10.0	10.0	10.0
c_4 [$/min]	250	250	250
$n_v^{\omega_1}$	10	10	10
$n_v^{\omega_2}$	8	8	10
$n_v^{\omega_3}$	9	9	10
d_{ϕ_1}	1.00	1.00	1.00
d_{ϕ_2}	0.95	0.95	0.95
d_{ϕ_3}	0.90	0.90	0.90
Traffic model	TFF-1	TFF-2	TFF-2

TABLE II TSP models

Attribute	TSP-1	TSP-2	TSP-3	TSP-4	TSP-5	TSP-6	TSP-7
$\hat{\zeta}$ [hh:mm]	07:50	07:50	07:50	07:50	07:50	07:50	07:50
$\hat{T}_D$ [min]	{5, 5, 3, 3}	{5, 5, 3, 3}	{5, 5, 3, 3}	{5, 5, 3, 3}	{5, 5, 3, 3}	{5, 5, 3, 3}	{5, 5, 3, 3}
$\hat{T}_R$ [min]	{8, 70, 7}	{8, 70, 7}	{6, 65, 5}	{6, 65, 5}	{8, 70, 7}	{8, 70, 7}	{8, 70, 7}
$\hat{c}$ [$]	1600	1600	1600	1600	1600	1600	1600
ρ_δ	0.5	0.9	0.9	0.5	0.5	0.5	0.5
ρ_{T_D}	1.0	0.1	0.1	1.0	1.0	1.0	1.0
ρ_{T_R}	0.9	0.5	0.5	0.9	0.9	0.9	0.9
ρ_c	0.2	1.0	1.0	0.2	0.2	0.2	0.2
f_{ω_1}	1.0	0.0	0.0	0.0	0.4	0.0	0.0
f_{ω_2}	0.6	0.6	0.6	0.6	0.6	0.6	0.0
f_{ω_3}	0.0	1.0	1.0	1.0	1.0	1.0	1.0
f_{ϕ_1}	1.0	1.0	1.0	1.0	1.0	1.0	1.0
f_{ϕ_2}	0.8	0.9	0.9	0.9	0.9	0.9	0.9
f_{ϕ_3}	0.0	0.8	0.8	0.8	0.8	0.8	0.8
τ	0.1	0.1	0.1	0.1	0.1	0.1	0.1

TABLE III Simulation cases

Study	**Cases**	**IP-Model**	**TSP-Model**
1	1	IP-1	TSP-1
	2	IP-1	TSP-2
2	3	IP-2	TSP-2
	4	IP-2	TSP-3
	5	IP-2	TSP-4
3	6	IP-3	TSP-5
	7	IP-3	TSP-6
	8	IP-3	TSP-7

TABLE IV Track and station data

Track	**Origin**	**Destination**	**Length [km]**	**Track specific constant** A_i
1	Station A	Station B	20	1.2
2	Station B	Station C	200	1.0
3	Station C	Station D	15	1.1

TABLE V Simulation results for study 1

Category	Attribute	Case 1	Case 2
Track access right	ζ [hh:mm]	07:52	07:50
	T_D [min]	{6, 6, 3, 3}	{4, 4, 3, 3}
	T_R [min]	{9, 72, 8}	{8, 72, 8}
	c [$]	1783	1698
	ω	ω_2	ω_2
	ϕ	ϕ_2	ϕ_3
Constraint set in final round	ζ [hh:mm]	[07:50|07:52]	[07:50|07:51]
	T_D [min]	[5|6, 5|6, 3|3, 3|3]	[4|7, 4|7, 3|4, 3|4]
	T_R [min]	[8|9, 69|72, 7|8]	[8|9, 69|72, 7|8]
	c [$]	[0|1800]	[0|1700]
IP Utility	U [$]	1651	1524
	TUC [$]	113	113
	TEC [$]	567	567
	PDC [$]	130	90
	CGC [$]	974	926
	$\Delta\eta$	0.0166	0.0215

TABLE VI Simulation results for study 2

Category	**Attribute**	**Case 3**	**Case 4**	**Case 5**
Track access right	ζ [hh:mm]	07:50	07:50	07:50
	T_D [min]	{5, 5, 3, 3}	{5, 7, 3, 3}	{5, 5, 3, 3}
	T_R [min]	{8, 70, 7}	{6, 68, 6}	{6, 67, 6}
	c [$]	1634	1649	1664
	ω	ω_2	ω_2	ω_2
	ϕ	ϕ_3	ϕ_3	ϕ_3
Constraint set	ζ [hh:mm]	[07:50|07:51]	[07:50|07:51]	[07:50|07:51]
in final round	T_D [min]	[5|6, 5|6, 3|4, 3|4]	[5|7, 5|7, 3|4, 3|4]	[5|5, 5|5, 3|3, 3|3]
	T_R [min]	[8|8, 70|71, 7|7]	[6|7, 65|68, 5|6]	[6|7, 65|67, 5|6]
	c [$]	[0|1650]	[0|1650]	[0|1700]
IP Utility	U [$]	1541	1478	1487
	TUC [$]	113	113	113
	TEC [$]	576	580	588
	PDC [$]	80	80	90
	CGC [$]	865	872	873
	$\Delta\eta$	0.0093	0.0170	0.0186

TABLE VII Simulation results for study 3

Category	Attribute	Case 6	Case 7	Case 8
Track access right	ζ [hh:mm]	07:50	07:50	07:50
	T_D [min]	{5, 5, 3, 3}	{5, 5, 3, 3}	{5, 5, 3, 3}
	T_R [min]	{8, 70, 7}	{8, 71, 7}	{8, 70, 7}
	c [$]	1657	1748	1845
	ω	ω_1	ω_2	ω_3
	ϕ	ϕ_3	ϕ_3	ϕ_3
Constraint set in final round	ζ [hh:mm]	[07:50|07:50]	[07:50|07:51]	[07:50|07:51]
	T_D [min]	[5|5, 5|5, 3|3, 3|3]	[5|5, 5|5, 3|3, 3|3]	[5|5, 5|5, 3|3, 3|3]
	T_R [min]	[8|8, 70|70, 7|7]	[8|8, 70|71, 7|7]	[8|8, 70|71, 7|7]
	c [$]	[0|1700]	[0|1750]	[0|1850]
IP Utility	U [$]	1564	1639	1752
	TUC [$]	94	188	282
	TEC [$]	608	603	608
	PDC [$]	90	90	90
	CGC [$]	865	866	865
	$\Delta\eta$	0.0093	0.0108	0.0093